Exploring the Gamma Ray Horizon with the next generation of Gamma Ray Telescopes. Part 1: Theoretical predictions.

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Abstract

The physics potential of the next generation of Gamma Ray Telescopes in exploring the Gamma Ray Horizon is discussed. It is shown that the reduction in the Gamma Ray detection threshold might open the window to use precise determinations of the Gamma Ray Horizon as a function of the redshift to either put strong constraints on the Extragalactic Background Light modeling or to obtain relevant independent constraints in some fundamental cosmological parameters.

1 Introduction

Imaging Cherenkov Telescopes have proven to be the most successful tool developed so far to explore the cosmic gamma rays of energies above few hundred GeV. A pioneering generation of installations has been able to detect a handful of sources and start a whole program of very exciting physics studies. Now a second generation of more sophisticated Telescopes is starting to operate and is providing already with new exciting observations. One of the main characteristics of some of these new Telescopes [1], is the potential ability to reduce the gamma ray energy threshold below $\sim 10 - 20$ GeV, helping to fill the existing observational energy gap between the detector on satellites and the ground-based installations.

In the framework of the Standard Model of particle interactions, high energy gamma rays traversing cosmological distances are expected to be absorbed by their interaction with the diffuse background radiation fields, or "Extragalactic Background Light" (EBL), producing e^+e^- pairs. The $\gamma_{HE}\gamma_{EBL} \to e^+e^-$ cross section is strongly picked to $E_{CM} \sim 1.8 \times (2m_ec^2)$ and therefore, there is a specific range in the EBL energy which is "probed" by each gamma ray energy [2].

This effect should lead to the existence of a "Gamma Ray Horizon", limiting the feasibility of observing very high energy gamma rays coming from very far distances. The actual value of this horizon distance for gamma rays of a given energy, depends on the number density of the diffuse background radiation of the relevant energy range, which is traversed by the gamma rays. In the range of gamma ray energies which can be effectively studied by the next generation of Gamma Ray telescopes (from, say, 10 GeV to 50 TeV), the most relevant EBL component is the ultraviolet (UV) to infrared (IR) contribution.

Several models have been developed to try to predict that EBL density [3, 4]. These models do a quite complex convolution of the measurements of star formation rate, initial mass function and dust and light recycling history. The result is a set of relatively model-independent predictions which accuracy is improving as the quality of their astrophysics inputs improves with the new deep-field observations and which fits reasonably well the existing data.

Therefore, quantitative predictions of the Gamma Ray Horizon have already been made but, unfortunately, so far no clear confirmation can be drawn from the observations of the present generation of Gamma Ray Tele-

scopes.

On the one hand, some very high energy gamma ray events might have been observed from Mkn 501, a blazar at redshift $z \sim 0.03$ [5]. The mere observation of these events would somehow contradict the above predictions indicating, might be, the presence of a new mechanism violating the forementionned gamma-gamma reaction threshold, for which, for instance, Lorenz-Invariance violation has been advocated, as we'll discuss later. Unfortunately, the statistics is scarce and for these events the actual systematic uncertainty in the energy determination might be large and hence the situation remains somewhat unclear. On the other hand, for the handful of presently well established extragalactic sources (all of them at modest redshifts), no clear observation of a common energy cutoff which could be attributed to the gamma absorption in the intergalactic medium instead of simply to internal source characteristics, has been established so far. Nevertheless, for Mkn 501 a clear exponential energy spectrum cutoff has been observed and, under the assumption that its origin is the EBL absorption, upper limits on the EBL density in agreement with the expectations have been placed [6].

The fact that the new generation of Cherenkov Telescopes will reach a considerably lower energy threshold than the previous one should be of paramount importance in improving the present experimental situation for, at least, two reasons:

- Lower energy points with a much smaller uncertainty, due to the steep spectra, will be added to the spectra of the already observed sources allowing to disentangle much better the overall flux and spectral index from the cutoff position in the spectrum fit.

- Sources at higher redshift should be observable, giving a stronger lever arm in constraining the predictions and the possibility of observing a plethora of new sources that will allow unfolding the emission spectra and the gamma absorption.

The goal of this work is to analyse the physics potential of this new generation of telescopes in the measurement of the Gamma Ray Horizon and more specifically its impact in the understanding of the various models and parameters involved in its predictions. For this, the work is structured in two parts.

The first part, which is the one covered in the present paper, concerns the theoretical predictions. In this part, first the definition of the terms used in this work and their calculational procedure are reviewed in detail. Then, the theoretical predictions obtained for the Gamma Ray Horizon for different EBL approaches and also for different cosmological parameter sets are presented. Finally plausible scenarios that could effect the Gamma Ray Horizon predictions are commented. The actual sensitivity to these models and parameters is discussed.

The second part, which will be presented in a fore-coming paper, will deal with the prospective on what the experimental scenario might look like and a discussion on how much one can expect to pinpoint the parameters of the theory (with special emphasis on the cosmological ones)in the extrapolated data scenario.

2 Description of the calculation

In this section the detailed calculation of the Gamma Ray Horizon in terms of the predicted EBL density spectra is presented. Our strategy has been performing the complete calculation without any approximation by using a numerical integration approach. Different ansatzs for the calculation of the EBL predictions have been also analysed to see their impact on the Gamma Ray Horizon prediction. Also, the dependence on all the intervening parameters has been kept explicit to be able to track the effect of the different hypotheses in the final prediction.

The optical depth can be written with its explicit redshift and energy dependence[7] as

$$\tau(E,z) = \int_0^z dz' \frac{dl}{dz'} \int_0^2 dx\, \frac{x}{2} \int_{\frac{2m^2c^4}{Ex(1+z')^2}}^{\infty} d\epsilon \cdot n(\epsilon, z') \cdot \sigma[2xE\epsilon(1+z')^2] \qquad (1)$$

where $x \equiv 1 - \cos\theta$, E is the energy of the γ-ray,ϵ is the energy of the EBL photon, z is the redshift of the considered source and $n(\epsilon, z')$ is the spectral density at the given z'.

The predicted value of the optical depth depends on several physical parameters. A part from the dependence on the actual absorption process, which enters through the gamma-gamma cross section, and the direct dependence on the cosmological parameters H_0, Ω_M, and Ω_Λ introduced by the

geodesic radial displacement function, the spectral energy density is also an input parameter.

There exists observational data with determinations and bounds of the background energy density at $z = 0$ for several energies [8]. The determinations come from direct measurements of the EBL density using instruments on satellites whereas the bounds, happen mostly in the infrared part of the EBL and come from extrapolations using galaxy counting. Given the difficulty of observing "cold galaxies" due to the zodiacal light background, they provide just lower limits.

Several models, which fit the observational data of $n(\epsilon, z = 0)$, have been suggested [3] (a set of predictions for the most significant models can be seen in figure 2). These models do not provide all the necessary information for our calculation: they provide a description of spectral density at $z = 0$ while we need to know also the evolution of $n(\epsilon)$ as a function of z.

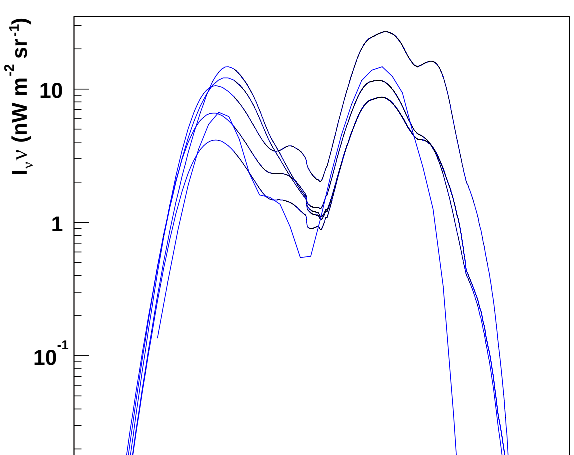

Figure 1: Model predictions for the energy density spectra at $z = 0$.

In this note three different approaches, which represent somehow limiting cases in the complexity of the ansatz assumed, for the z evolution of the EBL

have been used. Their comparison should give a feeling on how much the predictions change with the complexity of the theoretical assumptions and, hence, they might provide a tool to estimate how large the theoretical uncertainties in the final predictions might be. Ordered in increasing complexity, these approaches are:

1. Burst of star formation at high redshift [9].
2. Parameterisation of the measured star formation rate [9].
3. Star formation rate and star evolution [10].

Computing the GRH for these extreme scenarios allows us to get an estimation of its maximum uncertainty due to the unprecise EBL knowledge.

2.1 Gamma Ray Horizon

For any given gamma ray energy, the Gamma Ray Horizon is defined as the source redshift for which the optical depth is $\tau(E, z) = 1$. Therefore, the Gamma Ray Horizon gives, for each gamma ray energy, the redshift location z of a source for which the intrinsic gamma flux suffers an e-fold decrease when observed on Earth $z = 0$ due to the gamma-gamma absorption.

In practice, the cut-off due to the Optical Depth is completely folded with the spectral emission of the gamma source. But on the other hand, the suppression factor in the gamma flux due to the Optical Depth depends only (assuming a specific cosmology and spectral EBL density) on the gamma energy and the redshift of the source. Therefore, a common gamma energy spectrum behaviour of a set of different gamma sources at the same redshift is most likely due to the Optical Depth.

The goal of this note has been studying the effect of the cosmological parameters and the different spectral density models in the Gamma Ray Horizon predictions for the gamma ray energy region covered by the next generation of Gamma Ray Telescopes. The results of this study are presented in the next section.

3 Results

3.1 Optical Depth and Gamma Ray Horizon

As already mentioned, for any given energy of the gamma ray that travels through the universe, the probability of interaction with the EBL photons to create e^+e^- pairs has a strong dependence with the energy of the background photons. Roughly speaking, each gamma energy "probes" a different EBL photon energy and therefore, the trends of the EBL spectrum as a function of the photon energy ϵ as well as its redshift evolution are reflected in the Optical Depth as a function of gamma energy E.

In figure 2 the Optical Depth for gamma rays coming from a set of different redshifts are shown as a function of the gamma ray energy. As already mentioned, in the comoving frame, the $\gamma_{HE}\gamma_{EBL} \rightarrow e^+e^-$ reaction has the maximum probability when $E_{CM} = E\epsilon(1 - \cos\theta) \sim 1.8 \times (2m_e c^2)$. This means that the flat zone seen in figure 2 corresponds to gamma rays that interact mainly with EBL between roughly 0.2 eV and 1 eV (depending on the source redshift), where the density of EBL photons has a sharp break down (figure 2). On the other hand, while the gamma rays explore the peaks due to the star radiation and the absorption and reemission in the interstellar medium, the Optical Depth keeps increasing but with a non-constant slope.

In figure 3 (dotted line) the GRH that we get solving numerically the equation $\tau = 1$ is shown. On the one hand, it is clear that from redshift $z = 1$ onwards, it is quite flat, so that gammas of energy about < 30 GeV could reach the Earth from any distance in the observable universe. On the other hand the GRH depends strongly on the redshift for $z < 1$.

3.2 Spectral density

The Gamma Ray Horizon has been calculated for the three different evolutions of $n(\epsilon, z')$ already mentioned. For the first and second approaches ("Burst of star formation at high redshift" and "Parameterisation of the star formation rate") a model which defines the $n(\epsilon, 0)$ has to be chosen. In figure 3, a specific model for $n(\epsilon, 0)$ [3] and specific values for the Madau curve ($\alpha_M = 3.8$, $\beta_M = -1$, $z_b = 1.5$ and $z_f = 10$), which agree with recent data [11], have been used.

The third model, namely the "Star formation rate and star evolution"

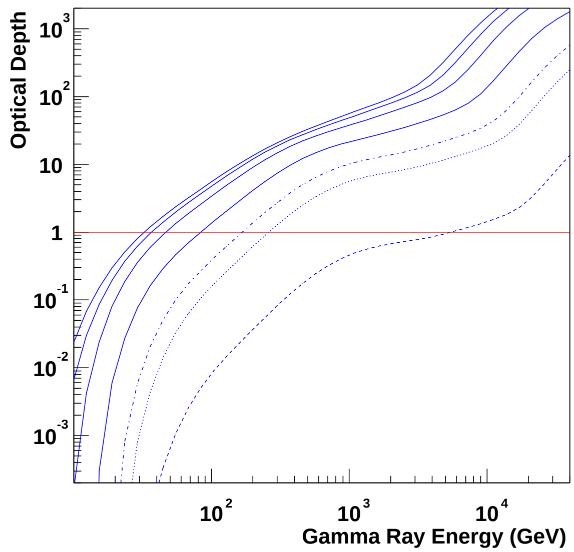

Figure 2: Optical depth for z = 0.03 (doted line), z = 0.3 (dashed line), z = 0.5 (dot-dashed line) and z=1,2,3,4 (solid lines). The intersection with the horizontal line (Optical Depth = 1) is the Gamma Ray Horizon.

assumption, is likely the closest to reality, so it is going to be used for all further studies in this work and, in fact, has already been used as a particular example in the previous sections.

The fact that we will stick to this approach and that no error bars are shown in figure 3, does not mean that this prediction is free from theoretical uncertainties. This model has a lot of inputs that come from cosmological measurements which have, in fact, quite large uncertainties [4]. For instance, if one would assume a fit to the star formation rate in the redshift region for $z > z_b$ as the classical Madau curve [12] instead of a slowly decreasing rate, this would produce a sizeable change in the GRH $(20 - 40$ GeV) prediction at large redshift. The uncertainty for low redshifts can be estimated by computing the GRH for several models of $n(\epsilon, 0)$, which produce a factor ~ 5 difference in the GRH energy prediction for $z << 1$ independently of the model used for its evolution.

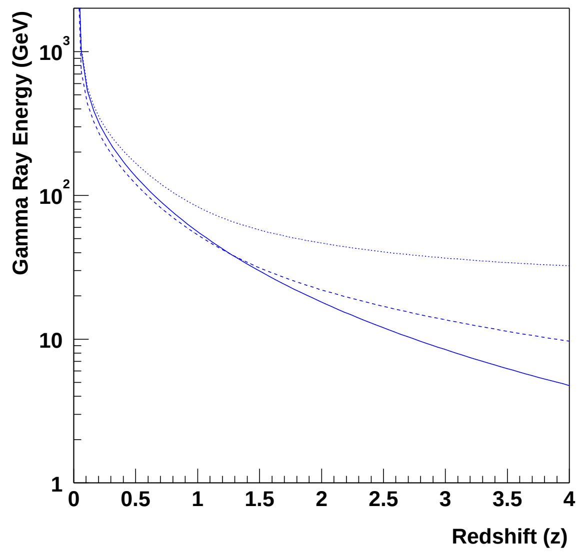

Figure 3: Gamma Ray Horizon for different approaches for the calculation of the z evolution of the EBL (see text): "burst of star formation" (solid line), "star formation rate" (dashed line), and "star evolution" (doted line).The cosmological parameters are fixed to $H_0 = 68$ Km s^{-1} Mpc^{-1}, $\Omega_M = 0.35$ and $\Omega_\Lambda = 0.65$.

3.3 Cosmological parameters

As we have already commented, some fundamental cosmological parameters such as the Hubble constant and the cosmological densities play also an important role in the calculation of the Gamma Ray Horizon since they provide the bulk of the z dependence of our predictions.

Over the last few years, the confidence in the experimental determinations of these cosmological parameters has increased dramatically. To understand the effect of moving these parameters, the values quoted in table 1 have been used.

Before we discuss the impact of each one of these parameters in our predictions we would like to see how actually the observables that we will measure (Optical Depths and GRH) depend on the redshift z to compare it with the

Parameter	Allowed range
H_0	72±4
Ω_Λ	0.72±0.09
Ω_M	0.29±0.07

Table 1: Best current fit values for cosmological parameters with 1 σ confidence level[13, 14].

redshift dependence of other observables. For that, we have plotted the prediction for their z evolution in figure 4. In that figure, for each observable it is shown the prediction normalized to the value at $z = 0.01$. For comparison, the z variation of the Luminosity-Distance, used for the determination of the cosmological parameters using Supernova 1A observations and of the Geodesical-Distance, giving the gamma ray path length, are shown. One can see that the Optical Depth has a quite different behaviour depending on the gamma ray energy explored. The z dependence is very pronounced at large redshifts for 20 GeV gammas and approaches a "Geodesical-Distance"-like shape for 2 TeV gamma rays. The reason for that is the actual shape of the EBL spectrum and its redshift evolution. To give a feeling of the actual average z dependence of the Optical Depth, the prediction for a flat νI_ν EBL spectrum is also shown. Finally, the z dependence of the inverse of the GRH energy is also shown.

Now, to understand up to which level the measurement of the GRH would allow to get information on H_0, Ω_Λ and Ω_M, the actual prediction of the GRH with the most sophisticated EBL approach has been repeated for a set of different values of these cosmological parameters.

For that, first each one of the parameters was changed $\pm 3\,\sigma$ from its best fit value, keeping the rest at their best fit value. The results are shown in figures 5 and 6. In figure 5, one can see that a $3\,\sigma$ variation leads to a change in the GRH prediction at high redshift which is of ~ 8 GeV for Ω_M and ~ 4 GeV for Ω_Λ, while keeping the GHR prediction unchanged at low redshifts as it was expected since for $z << 1$ the lookback time curve does not depend on Ω_M and Ω_Λ. Figure 6 shows that a $3\,\sigma$ variation on H_0 also leads to ~ 5 GeV difference at high redshift but there is now also a sizeable difference for low redshifts, in contrast to the behaviour in the previous case.

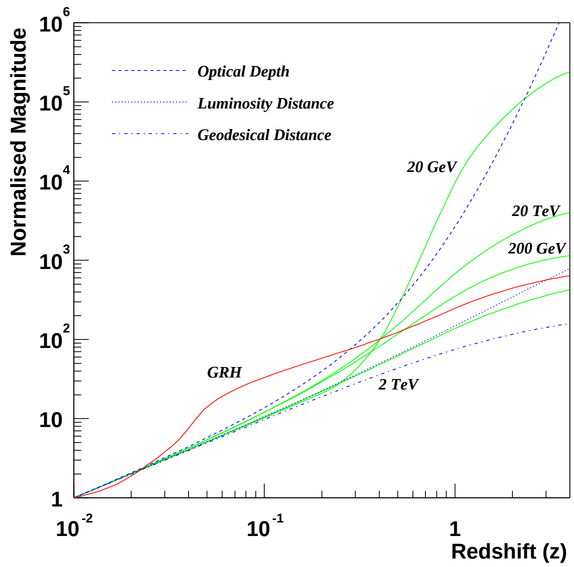

Figure 4: Redshift dependence of different observables. The predictions are normalized to their value at $z = 0.01$. The solid lines correspond to the Optical Depth prediction for gamma rays of different energies (20 GeV to 20 TeV) while the dashed line is the prediction for a flat νI_ν EBL spectrum. The GRH curve gives the z dependence of the inverse of the GRH energy.

The Hubble constant enters in the Optical Depth calculation as global factor and therefore its variation produces a global shift of the Optical Depth. Then, the flatest zone of the Optical Depth crosses the $\tau = 1$ line at different redshift, which is seen in the GRH as a region where the logarithm of the GRH energy as a function of the logarithm of the redshift shows a hard slope (figure 6). Therefore the zone close to the hard slope region is very sensitive to H_0, since a 3 σ variation changes $\sim$ 50% the GRH.

The fact that the variations in the GRH due to the Hubble constant and due to the cosmological densities are qualitatively different leaves some room to disentangle both kind of parameters. Actually, in figure 7 it can be seen that a $3\,\sigma$ difference in each parameter produces a change of around 10% in both cases at large redshift. But while decreasing redshift the effect due

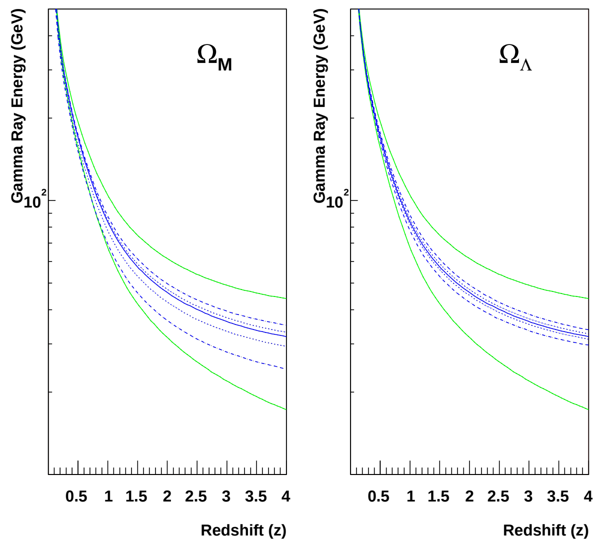

Figure 5: Gamma Ray Horizon for different values of the cosmological densities. In both plots the upper solid line is for $\Omega_M = 1$ and $\Omega_\Lambda = 0$ and vice versa for the lower solid line. The dashed lines are for $\pm 3\,\sigma$ and dotted lines are for $\pm 1\,\sigma$ according to the current best fit.

to changing the cosmological densities goes to zero, the effect due to the Hubble constant remains at around 8%. Therefore the precise determination of the GRH for $z < 0.1$ and for $z > 0.1$ will allow to perform independent measurement of both sets of parameters. In fact, above $z > 0.1$ also the dependence on Ω_Λ and Ω_M is different and therefore, precise measurements may provide a handle to measure both independently.

Finally, the sensitivity of the measurement of the GRH energy as a function of the redshift z on each one of the parameters varied independently while keeping the rest at their best fit value, has been computed and is plotted in figure 8. In that figure the sensitivity for each parameter p is actually defined as

$$S_p(z) \equiv p\, \frac{dE_{GRH}(z)}{dp} \tag{2}$$

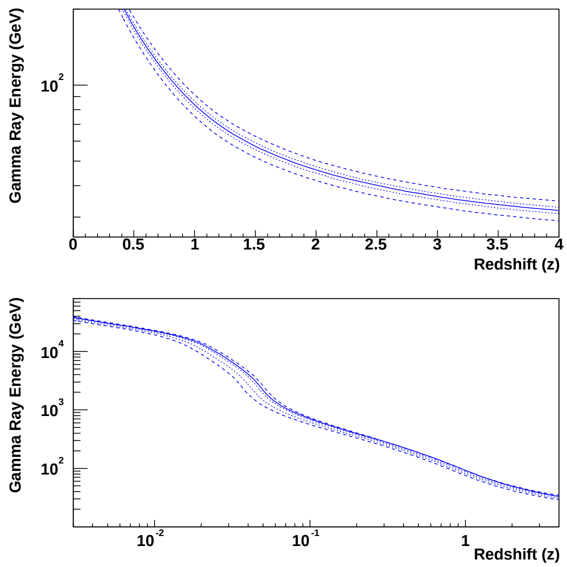

Figure 6: Gamma Ray Horizon for different values of the Hubble constant in linear and logarithmic redshift scales. The solid line is for the best fit values. The dashed lines are for $\pm 3\,\sigma$ and dotted lines are for $\pm 1\,\sigma$ according to the current best fit.

in such a way that for a given uncertainty in the estimation of the GRH energy ΔE_{GRH} the relative precision in the single-parameter determination of p would be

$$\frac{\Delta p}{p} = \frac{1}{S_p}\,\Delta E_{GRH} \tag{3}$$

It is clear that the maximal relative sensitivity is for the H_0 parameter while for Ω_M the relative sensitivity is, depending on the z region, between one and two orders of magnitude smaller and around a factor 5 even smaller for Ω_Λ. In this figure it is also clear that the sensitivities evolve differently with z and therefore, if precision measurements are obtained it should be possible to fit simultaneously the three parameters. This possibility will be explored in detail in the second part of this work already mentioned at the introduction.

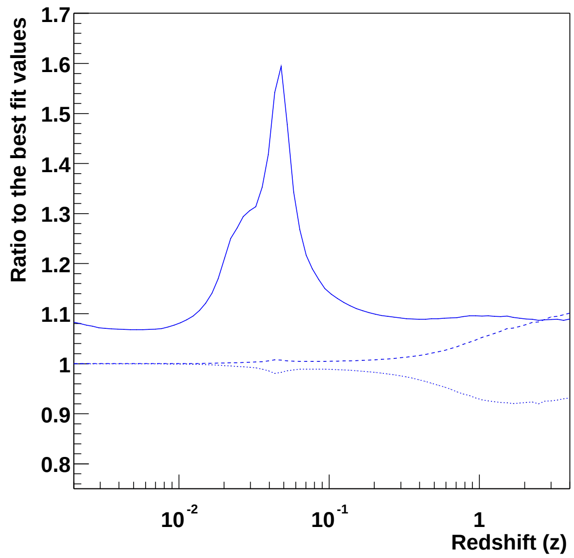

Figure 7: Ratio of the GRH for values of H_0 (solid line), Ω_M (dashed line) and Ω_Λ (dotted line) which are $3\,\sigma$ above the current best fit, over the GRH for the current best fit values

3.4 Beyond the "standard" calculation.

In the calculation presented above, the assumptions taken are based on our present knowledge of fundamental interactions, astrophysics and cosmology. Nevertheless, at such high energies and cosmological distances, for instance the effects from physics beyond the "Standard Model", such as Quantum Gravity or Supersymmetry, could be important.

There are plausible scenarios "beyond" the present knowledge which could affect the GRH prediction and hence, should be considered. In the following we would like to comment on our understanding on how these effects, and other effects not considered in our calculations, could change the GRH predictions presented above.

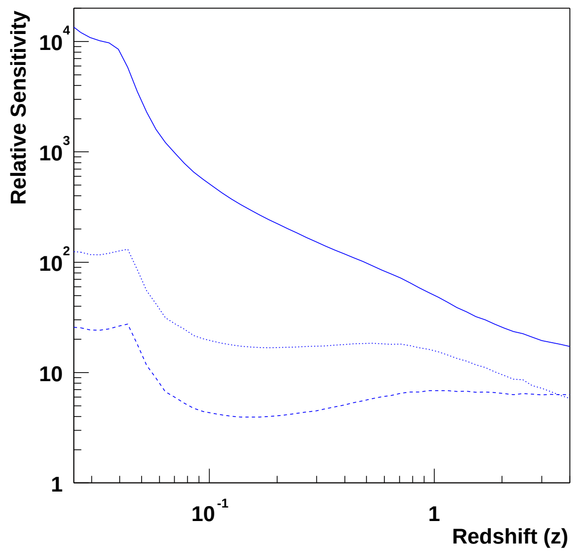

Figure 8: Sensitivity of the GRH energy to relative variations in H_0 (solid line), Ω_M (dashed line) and Ω_Λ (dotted line).

3.4.1 The absorption mechanism.

So far the only considered absorption mechanism has been the gamma-gamma interaction. As we have already seen, the gamma-gamma reaction has a strong dependence on the final state fermion mass and we have checked explicitly with our calculation that the contribution coming from Standard Model fermions other than the electrons adds a negligible absorption. As far as we know no extension of the Standard Model provides any alternative light final state particle not excluded already by the present accelerators that could add any significant amount of gamma-gamma absorption. Therefore, no sizable change in the GRH prediction can be expected in Standard Model extensions such a Supersymmetry due to modifications in the gamma-gamma cross section.

It is clear that the target for the high energy gammas could also be any other particle filling the intergalactic space. Therefore, it could be neutrinos, visible matter and barionic and non-barionic dark matter. Given the

expected density for these targets and the present constraints in the dark matter candidates, we are not aware of any absorption mechanism with these targets that could add any sizable absorption contribution to the one of the gamma-gamma reaction for the gamma ray energy range considered in this paper and hence, give any sizable correction to the GRH prediction.

3.4.2 Lorentz Invariance Violation.

High energy gamma rays traversing cosmological distances should notice the quantum fluctuations in the gravitational vacuum which unavoidably should happen in any quantum theory of gravitation. These fluctuations may occur on scale sizes as small as the Planck length $L_P \simeq 10^{-33}$ cm or time-scales of the order of $t_P \simeq 1/E_P$ ($E_P \simeq 10^{19}$ GeV).

These gammas will therefore experience a "vacuum polarization" correction which should be very small ($O(E/E_{QG})$ where E is the gamma energy and E_{QG} is an effective scale for Quantum Gravity, which might be as large as E_P but might become measurable after the gamma has traversed cosmological distances. In this Quantum Gravity scenario emerges naturally the requirement of local "violation" of the Lorenz-Invariance symmetry [15, 16] providing as a direct effect an energy-dependent propagation speed for electromagnetic waves.

This local "violation" of the Lorenz-Invariance symmetry changes the threshold condition for the $\gamma\gamma \rightarrow f^+f^-$ reaction in a way that depends on the Quantum Gravity model considered and its effective scale [17]. For plausible models, the correction to the GRH predictions turns out to be quite important and hence, deserves a detailed discussion, which we presented in reference [18].

3.4.3 Astrophysical considerations.

The gamma-gamma cross section depends strongly on the gamma polarization state. The calculation made in this paper assumes unpolarized gammas but it might happen that the specific gamma ray source producing the high energy gammas under study produces them with a non-negligible degree of polarization. If that is the case, the cross section could change in such a way that the GRH could differ from the above predictions for that specific source.

Similarly, in the whole calculation it has been assumed that the distribution of the EBL was uniform and isotropic at any scale. Given the fact that we consider cosmological distances this assumption is quite plausible. Nevertheless, for any specific gamma ray source, it might happen that the "local" EBL density might differ sizably from the "average" one and therefore, the GRH observed from that source could be sizably different from our prediction.

These aspects and other of similar kind depending on the specific characteristics of the source and its environment should be easy to disentangle from the fundamental predictions if enough sources are observed at each redshift location range.

4 Conclusions

A complete calculation of the Gamma Ray Horizon (GRH) in the gamma ray energy range which will be covered by the next generation of Gamma Ray Telescopes has been presented and discussed in detail.

Several approaches for the calculation of the extragalactic background light (EBL) density ranging in complexity have been compared. That comparison shows that the uncertainties due to the EBL modeling might be quite large both at low and high redshift. Nevertheless, the results for the most realistic approaches agree in predicting that the GRH energy at large redshifts is of ~ 30 GeV and, hence, should be on the reach of the next generation Cherenkov Telescopes.

Following these predictions, the observable universe should become transparent to gamma rays of below ~ 30 GeV and then new, high redshift, high energy gamma ray sources should be observable by the next generation Cherenkov telescopes [1].

If these new sources are abundant enough to make possible a precise measurement of the GRH energy as a function of the redshift, then either

[1] A different scenario but with a similar spirit was analysed in reference [19]. There, the energy threshold for the new generation gamma-ray detectors was assumed to be > 100 GeV, well above the asymptotic horizon given by the GRH predictions discussed here. Given this fact, to explore the cosmological potential that work does not use a direct measurement of the GRH but, instead, the observation of the halo radiation coming from secondary gamma emission in the electromagnetic cascade generated by the absolved primary VHE gammas

they can be used to place strong constraints in the EBL modeling or as a new technique allowing an independent determination of the cosmological parameters.

Exploring deeper this second scenario, the actual dependence of the GRH predictions on the cosmological parameters has been discussed in detail. This study shows the potential capability of a precise GRH energy determination as a function of the redshift z to disentangle the relevant cosmological parameters and provide competitive determinations.

A more quantitative study on the actual experimental possibilities to fit the cosmological parameters with the foreseen observations is presented in the second part of this work.

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